COSMO Priority Project: Aerosol-Cloud Interactions in ICON Model (ACLIIM) - Project Plan

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Summary

Recently, new aerosols inputs to ICON radiation scheme (ecRAD) were introduced. As part of PP CAIIR (Clouds and Aerosols Improvements in ICON Radiation scheme), three options are now part of ICON master version: the 2D prognostic AOD advection scheme, the 3D CAMS (Copernicus Atmosphere Monitoring Service) climatology and the 3D CAMS forecasted aerosols. Some aerosols-cloud interactions (ACI) were also part of the CAIIR PP such as the new DeMott (2015) heterogenous ice nucleation parametrization which uses the CAMS dust climatology as a nucleating particle. The new detailed 3D CAMS data now available in ICON opens more opportunities for a better evaluation of cloud droplets number concentrations (CDNC) which has a strong impact on cloud formation, cloud reflectivity impacting radiation fluxes and other model variables. The CAIIR PP also included the coupling of CAMS 3D aerosols (forecasted or climatology) with the Segal & Khain (2006) cloud droplets activation scheme (SK2006) – a task which was not yet accomplished. The first step would be to complete this task. However, the SK2006 has its limitations on aerosols types and sizes and lacks the complexity of internal aerosol mixing. Therefore, we plan to explore other models and approaches which can be tailored to CAMS aerosols species. This project will include wide range of validations and comparisons to other datasets and observations on both regional and global scales. Finally, completing the implementation of the mixed-phase Spectral Bin Microphysics (SBM) as a reference model is also planned.

Motivation

Cloud condensation nuclei (CCN) number concentration is a key factor in cloud formation and cloud dynamics. In a pristine atmosphere, water vapor can condensate over few particles making them larger in size (large effective radius R_{eff}). In that case cloud droplets number concentration (CDNC) will be small. As a result, the cloud reflectivity will be lower allowing more shortwave downward radiation to pass to the surface layers and on the other hand rain formation can occur in earlier stages of the cloud life (further reducing cloud albedo). Early precipitation can suppress energy build-up which is needed for severe thunderstorms (Rosenfeld et at. 2008). In a polluted environment where CCN number concentration are large, the available water vapor is split to more CCNs and as a result CDNC number concentrations are larger with smaller effective radius. This will make clouds optically thicker and change the radiative fluxes accordingly. This process can delay rain formation which allows energy to accumulate resulting in stronger updraft at later stages of cloud life (further increasing cloud albedo). As a result, thunderstorms with graupel and hail can form (Rosenfeld et at. 2008). Nevertheless, too many CCNs can suppress precipitation entirely in extremely polluted atmosphere due to very small droplets with radii smaller than the critical radius or due to the lack of available water vapor. The true dynamics is even more complex due to varied internal feedback between the processes.

The indirect effect of CDNC on radiative fluxes can be extremely significant. In the $T^2(RC)^2$ priority project, we have shown that surface shortwave radiation increases by $\approx 150\, W/m^2$ when CCN number concentration changes from $500\, cm^{-3}$ (resulting in an effective radius of $R_{eff} \approx 4\, \mu m$) to $50\, cm^{-3}$ ($R_{eff} \approx 9\, \mu m$). Another indirect ACI is the effect on autoconversion rate. The autoconversion is often parametrized as a function of the inverse second power of CDNC (Seifert and Beheng ,2001). Although CCN and CDNC are important for NWP and largely contribute to climate models' uncertainties, CDNC is sometimes simplified to a constant value (tuning parameter). A constant makes only sense in limited-area models (with a rather small but dominant land fraction). Global models would at least use two values, one for land and one for ocean. In more sophisticated approaches, CDNC is estimated from optical properties such as aerosol optical depth at 550 nm (AOD) as a proxy. This approach has several disadvantages. First, AOD defines the total radiation reduction due to aerosols absorption and scattering via a column of atmosphere. Hence, the translation to number concentrations at each model level is not straightforward. Second, it is not clear how to distribute the mass along the vertical axis. In ICON, this is solved by applying a fixed vertical exponential decay with a constant decay rate (another tuning parameter). However, it is obvious that aerosols profiles are constantly changed by atmospheric dynamics. Even if a climatological value is desired, the seasonal and spatial differences can cause relative errors with orders of magnitude when the simple fixed exponential profile is used. Third, AOD measurements usually combine contributions from all aerosols, and the partitioning into aerosols species is sometimes unknown, although algorithms which use different satellite channels can help making this distinction.

In the COSMO priority project CAIIR, new aerosols options were introduced as an input to ICON's ecRAD (Hogan and Bozzo, 2018) radiation scheme. As an alternative to the 2D Tegen climatology (Tegen et al., 1997), we introduced the 2D AOD advection scheme and the Copernicus Atmosphere Monitoring Service (CAMS) 3D aerosols. CAMS is an ECMWF service, which provides global air quality analysis and forecast including aerosols and other tracers (Morcrette et al. 2009). The model is based on IFS and has a coarser spatial resolution (40 km since 2016) but the same vertical resolution (137 levels since 2019). The output forecast lead time is 5 days with a 3-hours temporal resolution. 3D mixing ratios of 11 aerosols tracers are calculated: 3 size bins of mineral dust (DU), 3 size bins of sea salt (SS), sulphate (SU), hydrophobic and hydrophilic tracers of both black carbon (BC) and organic matter (OM). In 2017, ECWMF introduced the CAMS 3D climatology based on CAMS reanalysis between the years 2003-2014 with a 60 levels resolution (Bozzo et al. 2017, 2020). The new climatology was implemented in ICON and offers a monthly climatology of aerosols profiles. These new developments in ICON opens new opportunities for a revised CDNC scheme in ICON. The current scheme is based on Segal & Khain (2006). In this parametrization, CDNC is diagnosed by four numbers (4D look-up table: 4D-LUT): CCN concentration (range: 50 cm^{-1} to 6400 cm^{-1}), mode radius of CCN size distribution (range: 0.02 µm to 0.04 µm), geometric standard deviation of CCN size distribution (σ_g, range: 0.1 to 0.5) and updraft speed at cloud base (range 0.5 m/s to 5 m/s). The size range restrictions were claimed to be reasonable since particles outside this range have a neglectable contribution to the total number concentration (see sec. 3.1.1 in Segal and Khain, 2006). SK2006 used a 2000-bins microphysical parcel model over wide range of atmospheric conditions and cloud types including both stratiform and cumulus clouds. They showed that the most significant factor governing the resulted CDNC is the CCN concentration. SK2006 do not make any distinction between aerosol cases, because they assume that all aerosols are made of NaCl. They claimed that the chemical variability is of less importance, since the growth factor difference between NaCl and other compositions depends on the relation $(B/B_{NaCl})^{1/3}$, where B is the “chemistry” term in the diffusion growth equation. Due to the 1/3 power law, this term is often close to 1. The ICON implementation of SK2006 currently has a few simplifications. First, the CCN concentration is evaluated from the Tegen’s 2D AOD using assumed vertical profiles for mass, particle size and bulk density. The 5 species are combined to one aerosol number concentration using a weighting factor which is the soluble fraction (0.1 for dust and 0.9 for organics). The mode radius and geometric standard deviation are fixed to 0.03 µm and 0.3 respectively regardless of the underlying components. By this, the 4D-LUT is reduced to 2D-LUT. Moreover, the vertical windspeed is later fixed to 0.25 m/s, which finally reduces the 4D to a 1D-LUT, making CDNC depending solely on CCN concentration. An updraft speed of the mentioned magnitude is, maybe, reasonable for stratiform clouds but very much underestimating the values seen in cumulus clouds and in situations with deep convection (Malavelle et al., 2014). This assumption is already a severe restriction for global simulations in which the convective up- and down-drafts are not resolved, but it becomes even more problematic for convective-permitting resolutions (Terai et al., 2020).

Project’s objectives

A. Coupling of SK2006 droplets activation scheme with CAMS aerosols

The first goal of this project concerns the full 4D-LUT activation of SK2006 coupled to CAMS 3D aerosols (CSK scheme thereafter). In this respect, there is no technical difference between CAMS forecasted aerosols and CAMS climatology. CAMS aerosols size distributions (mode radius and geometric standard deviation) will be used specifically for each of the hydrophilic species noting that only some contribute to the outcome due to the size restrictions mentioned above. A revised effective size will be used as input to the LUT considering the soluble fraction of each species. As a first step, the SK2006 scheme will be called for each of the six hydrophilic species separately but if computational cost will be high, combination of species will be performed to reduce computations. We will also consider a more sophisticated effective updraft speed as an input to the LUT i.e. as was suggested in COSMO priority project $T^2(RC)^2$. Moreover, sub-grid contributions to the updraft velocity can also be included. The full model will be evaluated in terms of both the resulting CDNC values (compared to CDNC measurement as will be explained in detail in the next sections) and the CPU runtime consumption. If needed, a lower LUT dimension will be considered accordingly. The CDNC calculations are relevant for three model components in ICON: radiation (R_{eff}), microphysics and convection (autoconversion).

B. Developing of a new droplets activation scheme using pyrcel model

The second goal of this project is to propose a new droplets activation parametrization based on a more recent parcel model by Rothenberg and Wang

(2016). This model, also known as *pyrcel*, is an improved adiabatic cloud parcel model suggested by Nenes et al. (2001) and Seinfeld and Pandis (2006). They made use of the κ-Köhler theory in which κ is the aerosol hygroscopicity (Petters and Kreidenweis, 2007). The model solves numerically a closed system of 5 ordinary differential equations with a user defined composition of aerosols input. To run this model, apart from aerosols composition, one should provide the initial condition of the parcel, namely the updraft speed, pressure, supersaturation and temperature. Since the gird-scale saturation adjustment procedure in ICON restricts relative humidity to 100%, the supersaturation input during ICON model run will be taken from the first layer below cloud base (negative supersaturation). The model output is the CDNC fraction with a specification of the contribution from each aerosol. Since the large number of variables makes it hard to use a LUT approach, machine learning techniques may be used as an alternative application.

C. Validations and inter-comparisons with various observational data sets

The third target of this project is the validation and inter-comparison of our model results to observational data and available CDNC & CCN climatologies. We will compare not only the values of the CDNC on a global scale but also the model scores in terms of cloud cover, precipitation, radiation and surface temperature. Currently the MODIS CDNC climatology is implemented as an external data set. Therefore, the first step would be to compare the results from the CSK scheme and the parametrization based on pyrcel scheme with the MODIS climatology which is based on 13 years of Aqua-MODIS (Bennartz and Rausch, 2017). We note that CDNC data retrieved from satellites has systematic errors due to three assumptions: grid box homogeneity, liquid water content is assumed to increase linearly from cloud base to cloud top and a constant CDNC at all cloud heights (Bennartz and Rausch, 2017). Another recently published data set is the CCN based on CAMS reanalysis (Block et al., 2024). In this work, CAMS aerosols reanalysis (CAMSRA) between the years 2003-2021 were taken to compute 3D CCN densities with a κ-Köhler formulation. Only the 6 hydrophilic species (out from 11 CAMS tracers) were considered: SU, BC, OM and 3 bins of SS. Although the original CAMSRA has a 3-hour temporal resolution, only the 00:00 UTC value once a day is provided. As for day-to-day observational data, we now have the CDNC 2D data set retrieved from MODIS both Aqua and Terra instruments (Gryspeerdt et al., 2022). The data currently covers the years 2000-2020 with a 1° spatial resolution and a daily temporal resolution. In this work the authors covered several sampling strategies compared with flight campaigns (Gryspeerdt et al., 2022).

Apart from validation of the CDNC outcome as described above, we plan to evaluate the model's scores compared to observational data. In CAIIR project, we extensively validated surface radiation fluxes against observational data at the surface. We showed that the direct effect on radiation was positive for both CAMS climatology and CAMS forecasted aerosols. These results were achieved on the limited area mode over the East Mediterranean region. We also performed 2 months (January and July 2022) of global scale ICON runs with Tegen aerosols vs. CAMS forecasted/climatology. The monthly averages of the Top of Atmosphere (TOA) radiation fluxes compared to CERES satellite measurements showed surprisingly small direct aerosol effect. We know from studies done in the $T^2(RC)^2$ project, that this is not the case when including the indirect aerosol effect and allowing a much broader size-spectrum of cloud droplets depending on a different aerosol climatology. The indirect effect may locally alter solar and thermal irradiance by tens of percents, just through changing cloud reflectivity due to different particle density and effective radius. It will be interesting and important to see the effect of forecasted CAMS aerosols on radiation fluxes at TOA as well as at the surface. We will also evaluate the model’s sensitivity of forecasted precipitation to the new cloud droplets concentration through the autoconversion process. According results will be verified against Radar data available for the Israel domain and possibly also for Greece. Other model output such as surface temperature will be verified at regional and global scales.

D. Implementation of a new effective radius parametrization for shallow clouds

We will also address the effective radius of sub-grid scale (SGS) clouds due to shallow convection and introduce the Khain et al. 2019 scheme (KH2019). Currently, the effective radius of these clouds is defined similarly to the grid-scale clouds apart from the water content calculation. The KH2019 approach exploits the low variability of effective radius in horizontal directions compared to the vertical direction so as to calculate this variable. This parametrization has successfully been implemented into the COSMO model as part of the $T^2(RC)^2$ project.

E. Mixed-phase Spectral-Bin-Microphysics

One of the achievements of the CAIIR project was the implementation of the warm phase Spectral Bin Microphysics (SBM) scheme in ICON (Khain et al. 2015, Khain et al. 2022). The fourth goal of this project is to fully complete the implementation of SBM in ICON by adding the mixed-phase into the scheme. Due to its large number of particles bins, SBM is computationally costly model. Therefore, SBM is usually considered as pure scientific tool or as an offline benchmark model used to evaluate operational schemes such as the 1-moment and 2-moment microphysics schemes in ICON.

F. Investigation the impact of vertical resolution on clouds and radiation

Vertical resolution in NWP models plays a critical role in accurately simulating atmospheric processes, particularly cloud formation and radiative transfer. The vertical discretization of the atmosphere directly impacts the model's ability to resolve rather shallow structures and phenomena that are crucial for cloud microphysics and radiation budgets. Higher vertical resolution allows for a more precise representation of the atmospheric column, enabling a better capture of temperature and moisture gradients, which are fundamental to cloud formation processes. This improved resolution is particularly important in the planetary boundary layer (PBL) and near the tropopause, where rapid changes in thermodynamic properties occur over small vertical distances. Enhanced vertical resolution in these regions allows for more accurate simulation of convective processes, including the development of cumulus clouds and the formation of stratocumulus decks. The improved vertical resolution also enhances the model's ability to simulate atmospheric gravity waves, which play a role for vertical mixing and can influence cloud formation in certain regimes. Radiative processes are highly sensitive to the vertical structure of the atmosphere, particularly the distribution of water vapor, clouds, and aerosols. Increased vertical resolution enables more accurate calculation of radiative heating rates throughout the atmospheric column. Recent studies have shown that increasing vertical resolution from typical values of 50-100 levels to 150-200 levels can lead to significant improvements in cloud prediction, particularly for low-level clouds and marine stratocumulus. These improvements translate to better forecasts of surface temperature, precipitation, and radiative fluxes.

Actions proposed

1. Implementation of the 4D SK2006 droplets activation scheme coupled with CAMS aerosols - CSK (Task 1)
2. Development of a new cloud droplets activation parametrization for CAMS aerosols using pyrcel model - CPML (Task 2)
3. Comparisons of CDNC results with previous observational data sets and climatologies (Task 3)
4. Validation of ICON scores using different cloud nucleation schemes against observational measurements (Task 4)
5. Implementation of KH2019 parametrization of droplets effective radius in shallow convection clouds (Task 5)
6. Inclusion of mixed-phase in the Spectral Bin Microphysics scheme in ICON (Task 6)
7. Investigation of the vertical resolution impact on cloud formation and radiation effects (Task 7)

Description of individual tasks

Task L: Project leadership

Estimated resources: 0.1 FTE per year

Task 1: Implementation of the 4D SK2006 droplets activation scheme coupled with CAMS aerosols (CSK)

In Segal & Khain, 2006 (SK2006), cloud droplets number concentration (CDNC) at cloud base is determined by the properties of aerosols particle size distribution: number concentration, mode radius and geometric standard deviation (σ_g) and also by the updraft speed at cloud base. The values can be calculated by the parametrization or may be extracted from a 4D look-up table. In the course of PP $T^2(RC)^2$, a look-up table version was applied in the COSMO model. The aerosols input can be the Tegen AOD climatology with a fixed mode radius and σ_g (reducing the 4D table to 2D) and using the AOD value to define an exponential decay for the aerosols number concentration. Alternatively, in this task, we wish to use the number concentration taken from CAMS 3D forecasted/climatology aerosols. This approach will be regarded as CSK method (CAMS-Segal-Khain). The number concentration of droplets is used for evaluation of the effective radius of water clouds, which effects the radiation fluxes (the so-called "indirect radiative effect of aerosols"). There are two ways of calculating the droplet effective radius from the droplet number concentration. The first method is using a power law of the ratio liquid water content (LWC) over CDNC : $\overline{R_{eff}} = c_1 \left(\frac{LWC}{CDNC} \right)^{c_2}$, where c_1, c_2 are determined from the particle size distribution used in the microphysical scheme. The second one is valid for sub-grid scale clouds due to shallow convection, which will be discussed in task 5 hereafter. The new cloud number concentration is also used in the autoconversion of cloud water to precipitation and can change the results.

Therefore, we propose the following subtasks:

Subtask 1.1 Implementation of the full 4D-LUT SK2006 method for cloud droplets activation in ICON 1-mom microphysics scheme using the 3D CAMS climatology and forecasted aerosols. The new CDNC should be consistently effective for both radiation (R_{eff}) and microphysical scheme.

Subtask 1.2 Implementation of revised effective updraft speed as an input to SK2006.

Subtask 1.3 Sensitivity analysis and documentation of the effects/case studies.

Deliverables:

(08.2025, 0.25 FTE, Harel 0.2, Daniel 0.05) Implementation of SK2006 method in ICON 1-mom scheme with different aerosols inputs

(08.2025, 0.25 FTE, Harel 0.2, Daniel 0.05) Implementation of revised effective updraft speed as an input to SK2006

(08.2026, 0.1 FTE, Harel 0.1) Sensitivity analysis and case studies performed

FTEs altogether: Harel 0.5, Daniel 0.1

Estimated resources: 0.6 FTE

Status: Not yet done.

Task 2: Development of a new cloud droplets activation parametrization for CAMS aerosols using pyrcel model (CPML)

The *pyrcel* model (Rothenberg and Wang, 2016), is an adiabatic cloud parcel model based on the κ-Köhler theory. It simulates the cloud evolution given initial atmospheric conditions including the aerosols population. The user can also choose between a fixed updraft speed or a height- dependent updraft speed but the latter is not yet feasible. The model inputs are: aerosol composition, updraft speed, pressure, supersaturation (S) and temperature (CCN, w, p, S and t respectively). The model output is the CDNC fraction with a specification of the contribution from each aerosol. From ICON perspective, only the CDNC is needed. In contrast to the 4D-LUT of SK2006, this method has many more dimensions. In fact, if we include only the 6 hydrophilic species of CAMS aerosols (ignoring DU and hydrophobic BC and OM) the result will be a 10D-LUT. This complexity forces us to use a different approach. We propose to use Machine Learning (ML) techniques such as Fully Connected Neural Network (FCNN) by TensorFlow or PyTorch. First, we will have to run *pyrcel* with numerous combinations of initial conditions covering the full range of global atmospheric conditions relevant for cloud condensation. These runs will be stored as a database for training the ML-model. The resulting model will later be used as a plug-in model into ICON. The method described here will be referred as the CPML method (CAMS-pyrcel-Machine-Learning).

Therefore, we propose the following subtasks:

Subtask 2.1 Setup pyrcel on ECMWF HPC and perform several runs with different initial conditions. Calculate the runtime and CPU needed for a single experiment and evaluate the number of experiments needed to build a database for training the ML model.

Subtask 2.2 Run pyrcel with different combinations of initial conditions (CCN, w, p, S, t) and build a data base of CDNC values as a function of these parameters. A sensible range of these variables will be chosen to cover all physically reasonable values on the one hand but also to minimize computational cost. The increments of each variable will be chosen according to the computational budget.

Subtask 2.3 Train a ML model such as Fully Connected Neural Network (FCNN) with the mentioned values as features and CDNC as a target. A 70/15/15 percentage of the data will be randomly chosen as training/testing/validation data respectively.

Subtask 2.4 Plug-in of the trained ML model in ICON. Possibly the COMIN interface will be used.

Deliverables:

(08.2025, 0.1 FTE, Harel 0.1) Setup pyrcel on ECMWF HPC and perform several tests

(08.2026, 0.2 FTE, Harel 0.2) Run many pyrcel experiments with different initial conditions to create a database for ML training

(08.2027, 0.3 FTE, Harel 0.3) ML model training

(08.2027, 0.5 FTE, Harel 0.3, Daniel 0.2) Plug-in of the trained ML model in ICON

FTEs altogether: Harel 0.9, Daniel 0.2

Estimated resources: 1.1 FTE

Status: Not yet done.

Task 3: Comparisons of CDNC results with available observational data sets and climatologies

In this task we wish to examine the methods mentioned in tasks 1 and 2. The CDNC calculated with the CSK and the CPML methods will be compared with three datasets available. First is the MODIS climatology which has already been implemented into ICON. This 2D dataset (Bennartz and Rausch, 2017) is based on 13 years of Aqua-MODIS with a 1°x1° resolution. Although they reported up to 80% uncertainties in CDNC values compared to in-situ measurements, this dataset can serve as a sanity check for our methods. The second dataset is also based on satellite retrievals with 1°x1° resolution but this time from both Terra and Aqua instruments of MODIS. The dataset covers the years 2000-2020 with a 1-day temporal resolution (Gryspeerdt et al., 2022). We will check with these authors the possibility of extending the data to the years 2020-2024. The third dataset is based on CAMS reanalysis (Block et al., 2024). This is also a 2D 1-day resolution dataset but covering the years 2003-2021. CCN densities were calculated with a simplified κ-Köhler formulation including only the 6 hydrophilic species of CAMS: SU, BC, OM and 3 bins of SS. For this task, global ICON simulations will be performed for selected months.

Therefore, we propose the following subtasks:

Subtask 3.1 Comparison of CDNC averaged values computed with ICON using both CSK and CPML methods with the MODIS climatology on global scale runs for selected months.

Subtask 3.2 Validation of CDNC daily values computed with ICON using both CSK and CPML methods with the MODIS daily values on the global scale runs for selected test cases.

Subtask 3.3 Comparison of CDNC daily values computed with ICON using both CSK and CPML methods with the CAMS reanalysis daily values on the global scale runs for selected test cases.

Deliverables:

(08.2027, 0.15 FTE, Harel 0.15) Comparison of monthly averaged value against MODIS climatology

(08.2027, 0.1 FTE, Harel 0.1) Validation of the day-to-day results against MODIS daily dataset

(08.2027, 0.05 FTE, Harel 0.05) Comparison of the day-to-day results against CAMS reanalysis

FTEs altogether: Harel 0.3

Estimated resources: 0.3 FTE

Status: Not yet done.

Task 4: Validation of ICON scores using different cloud nucleation schemes against observations

This task is devoted to extensive verifiaction of model scores against measurments. Both methods mentioned in tasks 1-2 will be evaluated compared to ICON's default scheme. By means of the global scale runs, we wish to evaluate results against satelites observations i.e. from CERES. The horizontal resolution of these runs and the time period (not less than two months) will be defined during the project after allocating of the computational resources. The parameters we desire to evaluate are: surface and TOA radiative fluxes, surface temperature and cloud mask. We will verify the results also against ground base measurements taken in Israel and Greece. From these observational datasets, we will verify the surface radiation, 2m-temperature and precipitation. All results will be verified at a 1-hour temporal resolution. The chosen domain is the South-East-Europe domain (SEE) which covers both Israel and Greece and is run opreationaly at IMS. The horizontal resolution will be 2.8 km with 65 vertical levels. ICON results will be averaged to match with the coarser spatial resolution of CERES data. Our goal is to run the limited area mode for a 1-year period (the specific year will be chosen in a later stage).

Therefore, we propose the following subtasks:

Subtask 4.1 Global ICON runs for at least two months period (i.e. January and July) with 48 hours lead time. The model setups will be the default, but using CSK and CPML methods for CDNC parametrizations. Verifications against CERES (or other satellite data). We will also compare the results with T2m SYNOP observations.

Subtask 4.2 LAM ICON runs on SEE domain for 1 year for the above model setups.

Subtask 4.3 Verifications of the results in subtask 4.2 against ground based observational data for Israel (taken from the IMS database)

Subtask 4.4 Verifications of the results in subtask 4.2 against ground based observational data for Greece (taken from the HNMS database).

Deliverables:

(08.2027, 0.25 FTE, Harel 0.1, Euripides 0.15) Perform global runs and verify against CERES and SYNOP

(08.2027, 0.15 FTE, Euripides 0.15) Perform ICON-SEE limited area model runs for 1 year

(08.2027, 0.15 FTE, Euripides 0.15) Verification against OBS in IMS

(08.2027, 0.15 FTE, Euripides 0.15) Verification against OBS in HNMS

FTEs altogether: Harel 0.1, Euripides 0.6

Estimated resources: 0.7 FTE

Status: Not yet done.

Task 5: Implementation of KH2019 parametrization of droplets effective radius in shallow convection clouds

Subtask 5.1 In the shallow convection parametrization of ICON, the cloud-specific liquid water content and the effective radius of droplets are estimated for radiation transfer calculations. Based on the low variability of effective radius within clouds in horizontal directions compared to the vertical direction, we plan to introduce an alternative calculation of effective radius and liquid water content in sub-grid scale clouds due to shallow convection using the parametrizations developed in Khain et al. 2019, section 5. Accordingly, the effective radius profile above cloud base can be calculated using the theoretical profile of adiabatic liquid water content, using the number concentration at cloud base and assuming the increased effect of mixing with height. Further, the number- concentration above cloud base can be parametrized considering its decrease in cases of drizzle formation. Then, the liquid water content profile above cloud base can be calculated using the above effective radius and number concentration profiles. These parametrizations are valid only in case of non-precipitating or drizzling of shallow cumulus clouds, and therefore perfectly fit for the shallow convection parametrization of ICON. These parametrizations were implemented in the COSMO code several years ago. Although the effect was not found significant, we believe they should be tested in ICON as they have a solid physical basis.

Subtask 5.2 Sensitivity analysis and documentation of the effects/case studies.

Deliverables:

(08.2026, 0.4 FTE, Pavel 0.3, Alberto 0.1) Implementation of R_{eff} and LWC parametrization in shallow convection parametrization

(08.2027, 0.1 FTE, Pavel 0.1) Sensitivity analysis and case studies performed

FTEs altogether: Pavel 0.4, Alberto 0.1

Estimated resources: 0.5 FTE

Status: Not yet done.

Task 6: Inclusion of Mixed-Phase Spectral Bin Microphysics in ICON

Microphysical schemes determine the development and the live time of a cloud. Moreover, they determine its optical properties via the liquid water content and the effective radius, and hence influence the radiation transfer. The Spectral Bin Microphysics (SBM) is a state-of-the-art microphysical scheme (Khain et al., 2015). Due to significant computer resources needed to run the scheme, it is usually used for research purposes and test cases analyses. It is included in several models worldwide, such as WRF, SAM, HUCM, JMA-NHM, and the Goddard Cumulus Ensemble model. On July 2023, the warm-phase version of SBM was included in ICON master (Khain et al., 2022). The planned implementation of mixed-phase SBM will allow to perform test cases analyses in ICON. It will allow to identify the pros and cons of the existing microphysical schemes, including possible estimation of the steady state supersaturation instead of the currently used saturation adjustment. We propose the following subtasks:

Subtask 6.1 Inclusion of the mixed-phase SBM in ICON

Mixed-phase SBM is already partially implemented in a private ICON branch. In this subtask we plan to implement the missing parts of ice nucleation and CCN regeneration. Following this step, we plan to submit a merge request and implement the scheme in the master version.

Subtask 6.2 Mixed-phase SBM calibration

At the second stage, we will test and calibrate the mixed-phase SBM performance. Currently, SBM implementation in ICON suffers from significant underestimation of precipitation in real cases. In this subtask, we plan to investigate and solve this issue, and later to compare its results using idealized and real test cases with the 1M and 2M schemes under similar conditions.

Deliverables:

(08.2026, 0.4 FTE, Pavel 0.4) Inclusion of the mixed-phase SBM in ICON

(08.2027, 0.3 FTE, Pavel 0.3) Mixed-phase SBM calibration

FTEs altogether: Pavel 0.7

Estimated resources: 0.7 FTE

Status: Not yet done.

Task 7: Investigation of the vertical resolution impact on cloud formation and radiation effects

Although NWP models are primarily developed with an emphasis on the horizontal mesh size, the impact of vertical resolution is an exceptional topic that has been investigated and challenged relatively less (Skamarock et al., 2019; Deng, 2008; Lindzen and Fox-Rabinovich, 1989; Schmidt et al., 2024). The flexibility of ICON model regarding the choice of vertical levels makes it an exceptional resource towards the advancement of understanding the interrelation between the horizontal and vertical model structures, in analogy with current similar research at ECMWF (Sander et al., 2021). An investigation of the impact of different model discretization is proposed with an emphasis of low-level clouds (Inoue et al., 2015) and radiation effects over the eastern Mediterranean, mainly over marine areas. Such an endeavour might be considered as a complement to PP $T^2(RC)^2$ as well as PP UTCS (Avgoustoglou et al., 2015; Khain et al., 2021) and also to recent efforts towards the understanding the ICON model representation of clouds based on visible and infrared satellite observations (Geiss et al., 2021). All results are expected to be verified on a 1-hour temporal resolution. The chosen domain will be the South-East-Europe domain (SEE) which covers both Israel and Greece and is implemented opreationaly at IMS. The horizontal reference resolution will be 2.8 km with 65 vertical levels. Our goal is to run ICON LAM for selected cases along the period of former PP CAIIR in 2023 with progressively increased number of levels up to at least a factor of two. The runs will cover all five aerosol climatologies investigated in PP CAIIR. The results will be compared with the observations of synoptic stations as well as radio soundings and satellite products. The expected outcome of this investigation are recommendations for the refinement of vertical resolution over confined areas of exceptional operational interest, where this refinement may be realized either via standard ICON runs or by utilizing the nesting options of the model.

Subtask 7.1 Selections of cases and configurations along with literature investigation. Running ICON with the recommended setup for different vertical resolutions. The cases are going to be taken from the year 2023 as referenced in the PP CAIR results.

Subtask 7.2 Realize the comparisons and statistics with available synoptic observations, radio soundings and cloudiness available from satellite products.

Deliverables:

(08.2026, 0.3 FTE, Euripides 0.3) ICON model output and corresponding sensitivities associated with the chosen configurations. The tentative computer resources are expected ~10 million billing units in ECMWF Atos provided by HNMS.

(08.2026, 0.3 FTE, Euripides 0.3) Evaluation of the results along with the associated physical implications. Creation of an internal report to COSMO as well as a peer reviewed publication.

FTEs altogether: Euripides 0.6

Estimated resources: 0.6 FTE

Status: Not yet done.

Links to other projects or work packages

Task 1 was previously a part of CAIIR project. Since it was not completed in the CAIIR time span, it is transferred to ACLIIM project with a significant upgrade due to its importance and complexity. Sub-grid cloud processes also belong to the general treatment of sub-grid processes related to turbulence or convection (with are a matter, e.g., in the ConSAT action).

Risks and general comments

1. Allocation of computer resources for pyrcel runs and Machine Learning model training. An Alternative would be the IMS HPC.
2. As for each new development, the expected computational costs for operational application require some prior assessment.
3. A close collaboration with DWD is needed for integration in ICON's master.
4. The work on task 1 and 2 should be communicated with ECMWF and KIT to avoid duplicate work.
5. There is the usual risks of some preliminary degeneration of overall model performance at a first stage without tuning.
6. The time evaluation for each task is a approximation only.

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Task	Contributing scientist(s)	FTE - years	FTE per person	Start	Deliverables	Date of delivery	Preceding tasks
1.1	Harel Muskatel (IMS) Daniel Rieger (DWD)	0.25	H-0.2 D-0.05	01.09.2024	Implementation of SK2006 method in ICON 1-mom scheme with different aerosols inputs	31.08.2025	-
1.2	Harel Muskatel (IMS) Daniel Rieger (DWD)	0.25	H-0.2 D-0.05	01.09.2024	Implementation of revised effective updraft speed as an input to SK2006	31.08.2025	1.1
1.3	Harel Muskatel (IMS)	0.1	H-0.1	01.09.2025	Case studies and sensitivity analysis	31.08.2026	1.1
2.1	Harel Muskatel (IMS)	0.1	H-0.1	01.09.2024	Setup pyrcel on ECMWF HPC and perform several	31.08.2025	-
2.2	Harel Muskatel (IMS)	0.2	H-0.2 0.1-1st yr 0.1-2nd yr	01.09.2024	Run many pyrcel experiments with different initial conditions to create a database for ML training	31.08.2026	2.1
2.3	Harel Muskatel	0.3	H-0.3	01.09.2025	ML model training	31.08.202	2.2

Task	Contributing scientist(s)	FTE-years	FTE per person	Start	Deliverables	Date of delivery	Preceding tasks
	(IMS)		0.2-2nd yr 0.1-3rd yr			7	
2.4	Harel Muskatel (IMS) Daniel Rieger (DWD)	0.5	H-0.3 (0.1-2nd yr 0.2-3rd yr) D-0.2 (0.1-2nd yr 0.1-3rd yr)	01.09.2025	Plug-in of the trained ML model in ICON	31.08.2027	2.3
3.1	Harel Muskatel (IMS)	0.15	H-0.15 (0.05-2nd yr 0.1-3rd yr)	01.09.2025	Comparison of monthly averaged value against MODIS climatology	31.08.2027	1-2
3.2	Harel Muskatel (IMS)	0.1	H-0.1 (0.05-2nd yr 0.05-3rd yr)	01.09.2025	Validation of the day-to-day results against MODIS daily dataset	31.08.2027	1-2
3.3	Harel Muskatel (IMS)	0.05	H-0.05	01.09.2026	Comparison of the day-to-day results against CAMS reanalysis	31.08.2027	1-2
4.1	Harel Muskatel (IMS) Euripides Augoustoglou (HNMS)	0.25	H-0.1 (0.1-3rd yr) E-0.15 (0.05-2nd yr 0.1-3rd yr)	01.09.2025	Perform global runs and verify against CERES	31.08.2027	1-2
4.2	Euripides Augoustoglou (HNMS)	0.15	E-0.15 (0.05-2nd yr 0.1-3rd yr)	01.09.2025	Perform ICON-SEE limited area model runs for 1 year	31.08.2027	1-2
4.3	Euripides Augoustoglou (HNMS)	0.15	E-0.15 (0.05-2nd yr	01.09.2025	Verification against OBS in IMS	31.08.2027	1-2

Task	Contributing scientist(s)	FTE-years	FTE per person	Start	Deliverables	Date of delivery	Preceding tasks
			0.1-3rd yr)				
4.4	Euripides Augoustoglou (HNMS)	0.15	E-0.15 (0.05-2nd yr 0.1-3rd yr)	01.09.2025	Verification against OBS in HNMS	31.08.2027	1-2
5.1	Pavel Khain (IMS) Alberto de Lozar (DWD)	0.4	P-0.3 (0.2-1st yr 0.1-2nd yr) A-0.1 (0.1-1st yr)	01.09.2024	Implementation of R_{eff} and LWC parametrization in shallow convection parametrization	31.08.2026	-
5.2	Pavel Khain (IMS)	0.1	P-0.1	01.09.2026	Sensitivity analysis and case studies performed	31.08.2027	5.1
6.1	Pavel Khain (IMS)	0.4	P-0.4 (0.3-1st yr 0.1-2nd yr)	01.09.2024	Inclusion of the mixed-phase SBM in ICON	31.08.2026	-
6.2	Pavel Khain (IMS)	0.3	P-0.3 (0.1-2nd yr 0.2-3rd yr)	01.09.2025	Mixed-phase SBM calibration	31.08.2027	6.1
7.1	Euripides Augoustoglou (HNMS)	0.3	E-0.3 (0.2-1st yr 0.1-2nd yr)	01.09.2024	ICON model output and corresponding sensitivities associated with the chosen configurations	31.08.2026	-
7.2	Euripides Augoustoglou (HNMS)	0.3	E-0.3 (0.2-1st yr 0.1-2nd yr)	01.09.2024	Evaluation of the results along with the associated physical implications. Creation of an internal report to COSMO as well as a peer reviewed publication	31.08.2026	-
L	Harel Muskatel	0.3	H-0.3	01.09.202	Project leadership	31.08.202	-

Task	Contributing scientist(s)	FTE-years	FTE per person	Start	Deliverables	Date of delivery	Preceding tasks
	(IMS)			4		7	
All		**4.8**		**01.09.2024**		**31.08.2027**	

Estimated resources (in FTE per year) needed COSMO-year:

	<u>2024-2025</u>	<u>2025-2026</u>	<u>2026-2027</u>
Harel Muskatel	**0.7 FTEs**	**0.7 FTEs**	**0.7 FTEs**
Pavel Khain	**0.5 FTEs**	**0.3 FTEs**	**0.3 FTEs**
Euripides Augoustoglou	**0.4 FTEs**	**0.4 FTEs**	**0.4 FTEs**
Daniel Rieger	**0.1 FTEs**	**0.1 FTEs**	**0.1 FTEs**
Alberto de Lozar	**0.1 FTEs**	**0.0 FTEs**	**0.0 FTEs**
Total:	**1.8 FTEs**	**1.5 FTEs**	**1.5 FTEs**